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Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview

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ABSTRACT

The Air Resources Board (ARB) led a multi-division, multi-agency research effort to collect emissions data from two late-model heavy-duty transit buses in three different configurations. The objectives of the study were 1) to assess driving cycle effects, 2) to evaluate toxicity between new and "clean" heavy duty engine technologies in use in California, and 3) to investigate total PM and ultrafine particle emissions. Chassis dynamometer testing was conducted at ARB's Heavy-duty Emissions Testing Laboratory (HDETL) in Los Angeles. The impetus behind this work was to compare the emissions from transit buses powered by similar engines and fueled by Emission Control Diesel (ECD-1) and compressed natural gas (CNG). Three vehicle configurations were investigated: 1) a CNG bus equipped with a 2000 DDC Series 50G engine, 2) a diesel bus equipped with a 1998 DDC Series 50 engine and a catalyzed muffler, and 3) the same diesel vehicle retrofitted with a Johnson Matthey Continuously Regenerating Technology (CRT™) diesel particulate filter (DPF) in place of the muffler. The CNG engine was certified for operation without an oxidation catalyst. The diesel vehicle was fueled by ARCO (a BP company) ECD-1. The duty cycles were, 1) idle operation, 2) a 55 mph steady-state (SS) cruise condition, 3) the Central Business District (CBD) cycle, 4) the Urban Dynamometer Driving Schedule (UDDS); and 5) the New York City Bus Cycle (NYBC). Collection of PM over multiple cycles was performed to ensure sufficient sample mass for subsequent chemical analyses. Information on regulated (NO_x, HC's, PM, and CO) and non-regulated (CO_2, NO_2, gas-phase toxic HC's, carbonyl compounds, polycyclic aromatic hydrocarbons (PAH), elements, and elemental and organic carbon) emissions was collected. Size-resolved PM mass and number emission measurements were conducted and extracts from diesel and CNG total PM samples were tested in the Ames mutagenicity bioassay analysis. Some preliminary results were reported in [1].

Emissions of measured pollutants showed cycle dependence. The shortest cycle, the NYBC, resulted consistently in the highest g/mi emissions of all regulated, CO_2, and NO_2 (for the CRT) emissions for all three vehicle configurations. Diesel (OxiCat) total PM emissions were the highest, as expected, compared to the CRT and CNG configurations. But the CRT was able to achieve an average reduction of 85% across all cycles based on data uncorrected for tunnel blanks. The CNG without oxidation catalyst

resulted in the highest emissions of THC and CO relative to the diesel configurations. Total Diesel (OxiCat) NO_x levels were essentially unchanged by the CRT and were higher compared to the CNG. However, during the CNG re-test, total NO_x showed a considerable increase relative to earlier results. The CRT catalyst generated NO_2/NO_x fractions that ranged from 40 % to 50 % across all cycles. This is in contrast to the NO_2 emission fractions from the Diesel (OxiCat), which were in the single-digit percentage range.

This paper presents results for the regulated, NO_2 and CO_2 emissions for all cycles, except idle, and an overview of the entire project.

INTRODUCTION

The California Clean Air Act mandates the ARB to achieve the maximum degree of emission reductions from all on- and off-road mobile sources in order to attain the state ambient air quality standards. The identification of diesel PM as a Toxic Air Contaminant (TAC) in California prompted the development of ARB's Diesel Risk Reduction Plan [2]. Accordingly, the ARB is currently involved in a number of regulatory strategies focused on emissions reductions from on-road and off-road engines. A number of control measures for new and existing engines have been identified. One recommendation to reduce diesel PM emissions promotes the use of diesel particulate filters (DPF) and alternative fuels [3]. For instance, the South Coast Air Quality Management District (SCAQMD) has adopted new rules that promote the use of CNG technology for urban public transit bus fleets of 15 vehicles or more [4].

While the available research database on diesel and natural gas emissions is extensive, the specific comparison of equivalent technology from a toxicity standpoint has not been attempted. Thus, the present study complements previous work and offers supporting information for possible future rule making.

The project's objective was to obtain a "snap shot" of the in-use public transit bus fleet in operation in Los Angeles, California, rather than a fleet average. The selection of test vehicles was based on the composition of the exiting Los Angeles County Metropolitan Transit Authority (LAMTA) fleet which, as illustrated in Figure 1, is dominated by CNG buses without after-treatment. The diesel vehicles either operate with an oxidation catalyst or a DPF [5].

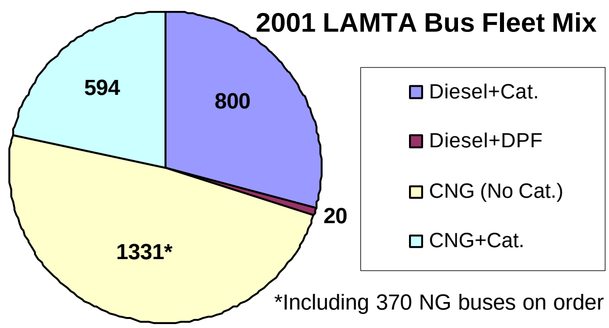

Figure 1. LAMTA Bus Fleet as of Nov. 2001.

EXPERIMENTS AND PROCEDURES

Testing Facility

Emission testing was conducted at ARB's HDETL located in downtown Los Angeles. The HDETL is equipped with heavy-duty engine and chassis dynamometers. Both are served by a common full exhaust flow dilution tunnel and feed into the same instrument sample train. The chassis dynamometer is a Schenck-Pegasus unit and utilizes a single 72 inch diameter roller. This dynamometer is driven by a direct current 675 hp motor that can absorb up to 660 hp. The range of simulated inertial weights is 5,000 to 100,000 lbs. The sampling system is a Horiba critical flow venturi, legislative constant volume sampler (CFV-CVS) capable of operation at four different flow rates. For this program, the CVS was operated at 2500 scfm. It consists of an 18 inch diameter primary dilution tunnel and a 5 inch diameter secondary dilution tunnel with heated lines for gas sampling. Primary dilution air is filtered through carbon and fiber material. A HEPA capsule was used to filter the secondary dilution air. A schematic of the experimental setup is illustrated in Figure 2.

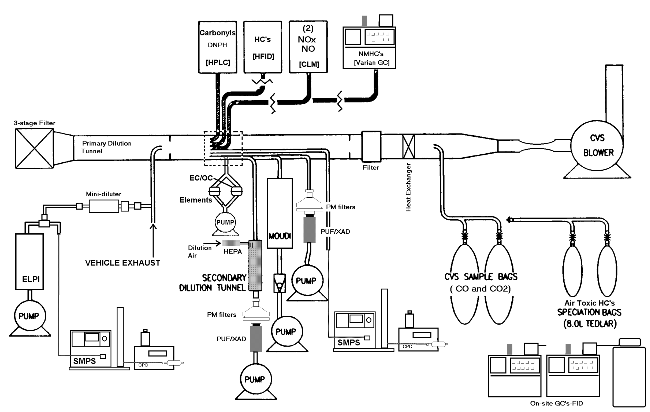

Figure 2. Schematic of dilution tunnel.

Vehicles and Cycles
Three vehicle configurations were investigated as is illustrated in Table A.1 in the appendix. These were, 1) a CNG 40-passenger New Flyer bus equipped with a 2000 DDC Series 50G engine, 2) a “baseline” diesel 40-passenger New Flyer bus equipped with a 1998 DDC Series 50 engine and a Nelson Exhaust System catalyzed muffler, and 3) the same diesel vehicle retrofitted with a Johnson Matthey Continuously Regenerating Technology (CRT™) DPF in place of the muffler. The CRT was installed new and de-greened prior to testing. The CNG bus was not equipped with any after-treatment system. The diesel vehicle was fueled by BP ARCO ECD-1. The vehicles were both procured from the LAMTA. Transient duty cycles included in this study were the Urban Dynamometer Driving Schedule (UDDS), the New York City Bus Cycle (NYBC), and the Central Business District (CBD) cycle. These are illustrated in Figures 3, 4, and 5, respectively, while Table 1 offers a comparison of the cycles. The SS 55 mph cruise was 20 min long for the “baseline” diesel (Diesel (OxiCat) in the legend) and 40 min for both the CNG and the CRT-equipped configurations. Equivalent cycle sequences composed of multiple cycles were run to ensure collection of sufficient sample. The NYBC and CBD have been described by Lanni, et al. in [6]. The UDDS refers to the U.S. EPA’s cycle developed for chassis dynamometer testing of heavy-duty vehicles. For the SS runs, the chassis dynamometer not only applied road load, but additional vehicle-specific load corresponding to approximately 60% of the available engine power. This condition was determined experimentally.

Chronologically, the CNG bus was tested first, followed by the diesel (OxiCat) and the CRT-equipped configurations. The CNG bus was re-tested after approximately 2 months in service. In the interim, the CNG vehicle had its O_2 sensor module replaced and engine software upgraded.

Table 1. Cycle Comparison.

	Steady State Cruise	CBD	UDDS	NYBC
duration (min)	20/40	10	17	10
distance (miles)	18/37	2	5.6	0.5
max. speed (mph)	55	20	58	30
ave. speed (mph)	55	6	19	1.5
cruise mode	Y	Y	Y	Y
idle mode	N	Y	Y	Y
accel. mode	N	Y	Y	Y

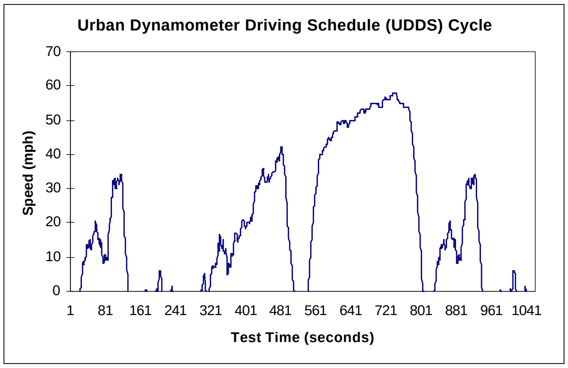

Figure 3. Urban Dynamometer Driving Schedule.

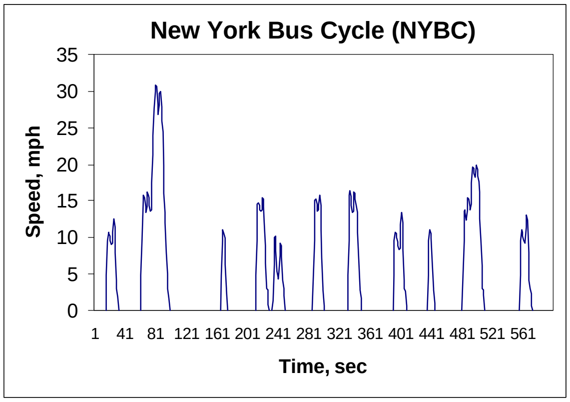

Figure 4. New York Bus Cycle.

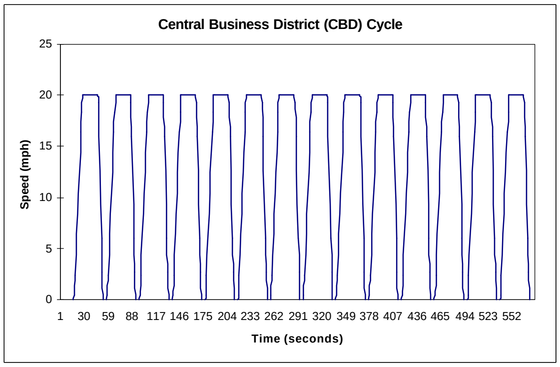

Figure 5. Central Business District Cycle.

Sample Collection and Analysis
Regulated Emissions - Gas samples were collected to determine total hydrocarbons (THC) and non-methane hydrocarbons (NMHC) for the diesel and CNG vehicles, respectively. Oxides of nitrogen (NO_x) and carbon monoxide (CO) emissions were collected and analyzed as shown in Table 2. Total PM samples were collected from the secondary dilution tunnel on standard 70 mm Teflon-coated filters. The standard legislative methods specified in the Code of Federal Regulations (CFR) were followed for the collection of regulated emissions samples. In addition, carbon dioxide (CO_2)

measurements were conducted for all tests and nitrogen dioxide (NO_2) emissions were determined primarily for the diesel vehicle. Two chemiluminescence (CLM) analyzers were used in parallel to determine NO_2 emissions as the difference between total NO_x and NO emissions. Due to the inherent differences between the CLM instruments and sampling trains used, response time delays had to be determined experimentally. A test vehicle and an external data acquisition system were used to determine delays. The data acquisition system was configured to record: 1) chassis dynamometer speed, 2) NO analyzer voltage output, and 3) NO_x analyzer voltage output. A series of accelerations were performed and the resultant voltage output from the CLM analyzers were recorded at 10 Hz. Analysis of the speed data versus the CLM response revealed a time delay of 10 sec for the instrument dedicated to NO_x measurements while the second analyzer dedicated to NO measurements had a time delay of 8 sec. The response time delays were verified during additional testing by switching the two CLM analyzers between the NO and NO_x modes. Subsequently, the time-stamped NO and NO_x output data for each test were realigned to take into account the response time delays before determining the final average NO_2 g/mi emissions on a cycle basis. The CFR method for calculating total NO_x emissions was used to determine NO_2 emissions.

Hydrocarbon Speciation - Speciation of toxic NMHC's was conducted from samples collected in Tedlar bags. Sample collection and analysis followed the NMOG procedure used by ARB for speciation of gasoline exhaust [7]. Briefly, VOC concentrations were determined using gas chromatography with a flame ionization detector following cryogenic pre-concentration. Table A.2 in the appendix illustrates the chief species of interest.

Carbonyls Compounds – Dilute exhaust from the primary dilution tunnel was drawn through Sep-Pak cartridges coated with 2,4-DNPH. Carbonyl compounds react with DNPH and form hydrazones. These are solvent extracted and analyzed by HPLC. Cartridge samples were collected for a single cycle in duplicate for all three vehicle configurations. Thirteen carbonyl compounds were analyzed. Table A.2 in the appendix illustrates the target analytes.

Organic and Inorganic Analysis - Additional PM samples were collected on 47 mm Teflon and quartz filter media from the primary dilution tunnel for subsequent inorganic and organic analyses, respectively. Elemental analysis was performed by X-Ray Fluorescence (ARB Method MLD034) while the content of elemental and organic carbon was determined based on the IMPROVE Thermal/Optical Analysis Method described by Chow et al. [8].

Bioassay Analysis – Dichloromethane (DCM) and sonication extractions for Ames bioassay analysis were obtained from the total PM 70 mm Pallflex Teflon filters after gravimetric mass analysis. Extractions were tested in the microsuspension procedure of the Salmonella/microsome assay as described by Kado et al. [9]. Tester strain TA98 and TA100 were used with and without the incorporation of microsomal enzymes (S9).

PAH Analysis – A two-stage sampler consisting of two 70 mm Pallflex Teflon filters and PUF/XAD adsorbents were used to collect PAH samples. The filters, PUF and XAD were analyzed separately. The filters were extracted with DCM, the PUF plug was extracted in acetone, and the XAD was extracted in DCM. Analyses followed those described in [9]. All sample extracts were concentrated and the extracts analyzed on a gas chromatograph/mass selective detector (GC/MSD) run in selective ion monitoring mode. Twenty-four PM-bound, volatile, and semi-volatile compounds were quantified ranging from naphthalene to benzo[ghi]perylene. Table A.2 in the appendix illustrates the target analytes segregated by phase.

Size-resolved Mass and Number Emissions - A 10-stage rotating Micro-orifice Uniform Deposit Impactor (MOUDI), an Electrical Low Pressure Impactor (ELPI), and two Scanning Mobility Particle Sizers (SMPS) were used for size-selective particle measurements. MOUDI samples were collected selectively on four stages using teflon. The size cuts were the 2.5, 0.56, 0.1, and 0.056 μm and the "catch-all" afterfilter. Two SMPS's were used to characterize particle size distributions at different sampling locations. One station was equipped with a partial-flow ejector-type mini-diluter for sampling raw vehicle exhaust using one SMPS and the ELPI. The second SMPS sampled a portion of the diluted exhaust directly from the CVS tunnel. This sampling point corresponded to the location where all other PM and gas samples were collected. Preliminary particle size distribution results are described in [1] and a forthcoming publication [10].

Table 2. Target Analytes, Collection, and Analysis.

Analyte	Collection Method	Analysis
Particle sizing	Continuous collection	SMPS
Size-resolved mass	MOUDI	Gravimetric
Mutagenicity	70 mm Pallflex T60A20 filters and PUF/XAD	Modified Ames bioassay
Polycyclic Aromatic Hydrocarbons (PAH)	Pallflex T70A20 Filter and PUF/XAD	GC/MS
Metals	47mm Teflon coated filters	X-Ray Flourescence (XRF)
Elemental Carbon/ Organic Carbon	47mm Quartz coated filters	Thermal/Optical Reflectance
Carbon Monoxide (CO) Carbon Dioxide (CO_2)	Tedlar Bag	Non-Dispersive Infrared Collection
Oxides of Nitrogen (NO_x)	Continuous collection	Heated Chemiluminescence (CLM) Detection
Total Hydrocarbons (THC)	Continuous collection	Heated Flame Ionization Detection (FID)
Particulate Matter	70 mm Pallflex T60A20 filters	Gravimetric Detection
Carbonyl Compounds	2,4-DNPH coated,-Silica Gel Cartridges	High Performance Liquid Chromatography (HPLC)
Volatile Organic Compounds	Tedlar Bag	GC-FID

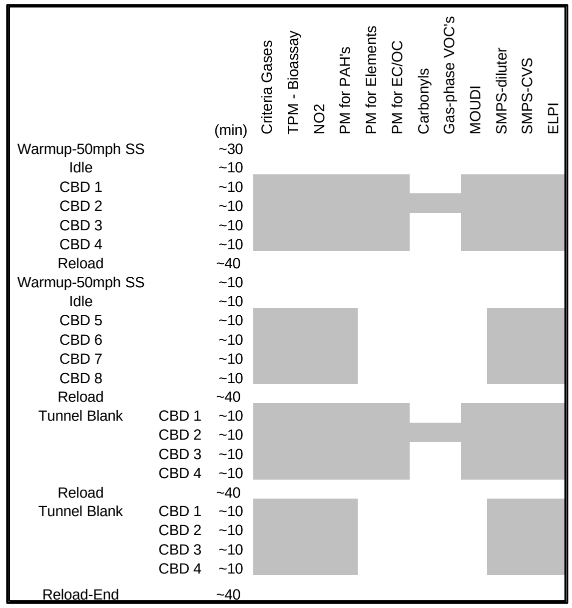

Figure 5. Test Protocol for CNG and CRT vehicles.

Testing Protocol

To ensure adequate sample loading for subsequent analyses, test sequences consisting of multiple cycles were used for all vehicle configurations. In addition, a tunnel blank for each test sequence was collected by sampling in the CVS tunnel for a total run time equivalent to that used for the cycle measurements. For tunnel blank tests, the bus exhaust inlet to the CVS tunnel was capped. The CBD test sequence for the CNG and CRT tests is illustrated in Figure 5. The shaded areas indicate the type of samples collected during each cycle repetition in a test sequence. For the CNG and CRT vehicles, 40 min test sequences were collected in order to yield sufficient sample. For the baseline diesel bus, 20 min sequences were sufficient. All samples were collected in duplicate. The buses were conditioned at the beginning of each test day for approximately 30 min by operating at 50 mph cruise. A test sequence followed initial conditioning typically after 10 min of idling. Samples were collected starting with the first cycle in a test sequence. All PM samples were composite samples over a single test sequence. Carbonyl compounds and VOC samples were collected only during the second cycle in a test sequence. The SMPS and ELPI were run continuously. A second test sequence was repeated to collect the duplicate sample.

RESULTS AND DISCUSSION

Fuel and Lubricating Oil Analyses

The ECD-1 diesel fuel was provided to the project by BP ARCO in two batches. A single sample from each fuel batch was analyzed by ARB and the results along with fuel specifications are illustrated in Table 3. The fuel samples were taken from fuel drums. In preparation for testing, the bus fuel tank was emptied, refilled with ECD-1, and operated on the dynamometer.

Table 3. Fuel Analysis, ECD-1 Diesel.

Property	***Sample-1***	***Sample-2***	***ECD-1 Specifications***	**Method**
Sulfur, ppm	11	11	15 max	D-5453
Aromatics, %v	20.9	20.9	20	D-5186
Aromatics, %wt	21.4	21.3		D-5186
PNA, %wt	2.78	2.76	3.2	D-5186
Centane Number			53.5	
Nitrogen, ppmw			30	
API Gravity			38	
Distillation IBP (D-86), deg.F			360	
Cloud Point, deg.F			14	
T10 (degC)	199	199		D-86
T50 (degC)	249	248		D-86
T90 (degC)	317	316		D-86
Density, g/mL	0.8285	0.8284		D-4052

The CNG fuel was obtained from refueling stations that normally supply the LAMTA fleet. The Southern California Gas Company provided assistance for sample collection and analysis. The natural gas fuel was analyzed for hydrocarbon speciation and sulfur content by two laboratories. Table 4 shows the results of these analyses. As indicated in the table, the first two samples were taken directly from the refueling station pump. The next three samples were collected directly from the CNG bus fuel tank. Typically, the fuel in the vehicle was a mixture from two different refueling stations supplying the LAMTA. Fuel analyses showed the quality of the natural gas consistently decreasing in time. The last sample collected when the bus was brought back for additional testing (CNG re-test) was slightly below specifications at a Methane No. of 77. The gross heating value for this sample was higher.

Table 4. CNG Fuel Analysis.

Specification / Analysis	(3/8/01) Sample 1	(3/8/01) Sample 2	(3/26/01) Sample 1	(3/26/01) Sample 2	(6/6/01) Sample 1	Specification
Methane, mole%	95.54	95.67	92.5	93.6	86.93	88.0 (min.)
Ethane, mole%	1.67	1.738	3.18	3.13	6.4	6.0 (max.)
C3 and higher / Propane, mole%	0.63	0.271	1.58	0.85	3.6	3.0 (max.)
CO2+N2, mole%	2.04	2.183	2.23	2.12	2.39	1.5-4.5 (range)
Oxygen, mole%	<0.01	0.027	0.18	0.01	0.12	1.0 (max.)
CO, mole%	<0.01		<0.01		<0.01	0.1 (max.)
Hydrogen, mole%	<0.01		<0.01		<0.01	0.1 (max.)
Total Sulfur, ppmv	1.7 (as H_2S)	0.93	1.8 (as H_2S)	4.77	1.3	16 (max.)
Gross Heating Value, BTU/cf	1017	1028.6	1046		1106	
Fuel Sample Source	Refuel. Stat.	Refuel. Stat.	Vehicle	Vehicle	Vehicle	
Methane Number					77	80

Lubricating oil samples were taken directly from the vehicles and analyzed for composition by a commercial laboratory before and after testing. Results are presented in Table 6. The before and after results for Fe and Viscosity show the typical engine wear and oil degradation expected. In addition, the measure of soot in the diesel vehicle oil samples suggests that replacement of the oil was needed. Although oil consumption was not measured, qualitative observations of engine oil fill levels during dynamometer testing did not reveal any unusual oil use for either of the two buses.

Table 6. Lubricating Oil Analysis.

	CNG-MTA#5300 start (3/12)	CNG-MTA#5300 end (3/26)	Diesel-MTA#3007 OEM start (4/16)	Diesel-MTA#3007 OEM end (5/1)	Diesel-MTA#3007 CRT equipped start (5/1)	Diesel-MTA#3007 CRT equipped 5/14)
Iron, ppm	2	3	17	19	19	21
Zinc, ppm	396	409	1390	1361	1361	1395
Phosphorus, ppm	291	306	1160	1121	1121	1165
Calcium, ppm	1120	1130	2578	2470	2470	2630
Copper, ppm	<1	2	1	1	1	2
Lead, ppm	1	1	2	2	2	2
Boron, ppm	1	1	6	6	6	6
Silicon, ppm	2	3	5	6	6	7
Viscosity (SUS)	536	509	478	476	476	473
Soot/Particulates*	normal	normal	severe	severe	severe	severe
Sulfur, %wt	0.529	0.541	0.3805	0.3843	0.3843	0.3864
Wear	Normal	Normal	Normal	Normal	Normal	Normal

** This proprietary qualifier denotes a normal, abnormal, or severe content of solid soot particles found in the samples. The parameter for analysis looks at oil "blackness."*

Regulated Emissions

The project is on-going and analyses of many of the non-regulated emissions results are in progress. These results will be reported in forthcoming publications. The regulated emissions results presented in this paper illustrate the average emissions collected over the multiple cycles in a test sequence. The same results are also summarized in Table A.3 in the appendix.

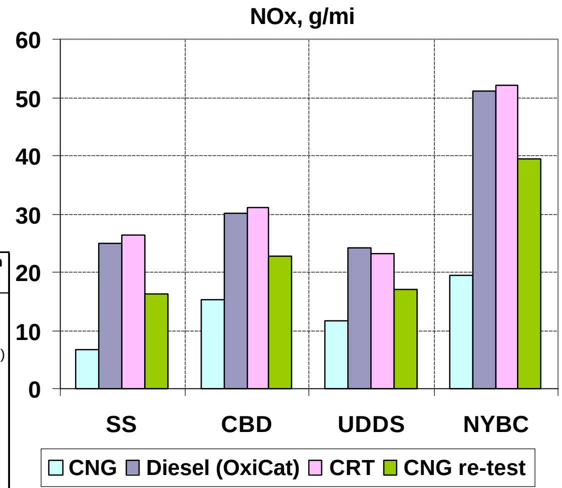

Figure 6. Average NO_x results.

Oxides of Nitrogen - Average NO_x emissions of 25 g/mi +/- 2 g/mi for the baseline (Diesel OxiCat) and CRT-equipped configurations were measured over both the SS and UDDS. The CBD values for both configurations were approximately 31 g/mi +/- 1 g/mi. The highest NO_x levels were observed over the NYBC cycle. These were 51 and 52 g/mi for the OEM and CRT configurations, respectively. Thus, total NO_x emissions remained essentially unchanged by the CRT. Results are presented in Figure 6.

The CNG bus was tested at the beginning of the project, sent back into fleet operation, and brought back to be re-tested after approximately 2 months in use. Surprisingly, the CNG bus NO_x emissions doubled over the SS and NYBC cycles; and increased by approximately 45% over the CBD and UDDS cycles. The maintenance records for this vehicle indicated that the engine software was upgraded and the O_2 sensor module was replaced. In addition, analysis of CNG fuel samples taken directly from the vehicle revealed that the natural gas used for the CNG re-test was slightly below specifications as discussed in the previous section. The fuel also contained a higher gross heating value than the previous samples. However, vehicle modifications or fuel quality may not necessarily explain the observed increase in gaseous emissions. Since variability of emissions rates from natural gas vehicles has also been observed by Clark et al., [11] and others, no precise explanation is offered at this time.

In general, the NYBC proved to be the most severe cycle and resulted in the highest NO_x emissions from all vehicle configurations. The CBD NO_x emissions were 64% of the NYBC emissions averaged across all four configurations. Similarly, the UDDS and SS NO_x emissions were comparable and only approximately 40% of the NYBC emission levels.

Particulate Matter - The effects of the CRT are evident in Figure 7, which shows average total PM results that have not been corrected for tunnel background. These are also summarized in Table 7. The trap showed the best performance over the CBD cycle where it reduced average emissions from 119 mg/mi to 14 mg/mi or better than 88%. The reduction efficiency over the SS was nearly 87%. That is, baseline emissions of 23 mg/mi were reduced to 3 mg/mi by the CRT. For the NYBC cycle, also the most rigorous driving schedule in terms of total PM emissions measured for all vehicle configurations, the 631 mg/mi average PM emissions for the Diesel (OxiCat) case were reduced by the trap to 96 mg/mi, an approximately 85% reduction. The smallest reduction occurred over the UDDS. For this cycle, 91 mg/mi emissions were reduced by 81% to 17 mg/mi. Again, it must be emphasized that these reductions are relative to the baseline case, which in this study was the diesel bus fueled by low-sulfur BP ARCO ECD-1 and equipped with a catalyzed muffler. Furthermore, these emissions results are uncorrected for tunnel background. Thus, the trap efficiencies described above may reflect the minimum rather than the absolute reduction capabilities of the CRT since, in some instances, the total PM levels measured during tunnel background tests were often at similar levels as the actual PM filter samples collected.

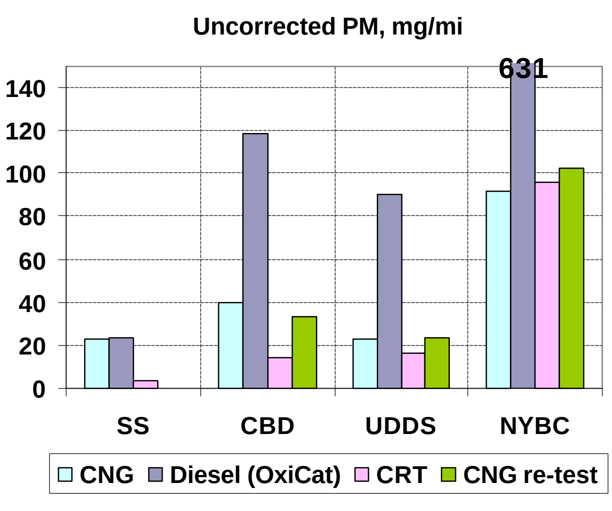

Figure 7. Average Total PM Emissions Uncorrected for Background.

Table 7. CRT Reductions Relative to Baseline. In the heading, Diesel OEM = Diesel (OxiCat).

Cycle	Total PM* Diesel OEM mg/mi	Total PM* CRT mg/mi	% Reduction Efficiency
SS	23.3	3.43	87
CBD	119.03	14.15	88
NYBC	631	95.9	85
UDDS	90.63	16.63	81

* Uncorrected for tunnel background

The effect of driving cycle on CNG total PM emissions was similar to the diesel results in that the NYBC cycle was also found to be the most severe on the CNG bus. Emissions of 92 mg/mi and 102 mg/mi for the CNG and CNG re-test, respectively, were measured over the NYBC cycle. These emissions rates are significantly higher than the 40 mg/mi and 33 mg/mi PM emissions for the same two vehicle configurations over the CBD. The UDDS and SS results were approximately 23 mg/mi for both CNG tests. The CNG re-test PM emissions for SS were not measured due to logistical problems. The variation in total PM emissions from the CNG to the CNG re-test were not consistent across cycles. This is in contrast to the NO_x emissions results reported previously, which were found to be higher for the CNG re-test over all cycles. Over the CBD, the CNG re-test showed an average PM reduction of approximately 16% relative to the earlier tests. Conversely, the PM emissions over the NYBC and UDDS increased by 11% and 3%, respectively.

In a relative comparison of fuels and aftertreatment, the CRT-equipped diesel bus showed an average PM emissions advantage over the non-catalyzed CNG bus across the CBD, UDDS, and the SS based on both the CNG and the CNG re-test results. Only the average NYBC PM results of 92 mg/mi for the CNG were slightly better than the CRT emissions of 96 mg/mi over the same cycle. However, the standard deviations for these results were 20 mg/mi collected over two replicate test sequences and 22 mg/mi collected over four replicate test sequences for the CNG and CRT, respectively. Each test sequence was composed of three back-to-back NYBC cycles. As illustrated in Table A.3, the standard deviations for the PM results over the NYBC cycle were uncharacteristically higher than the deviations in the results for the remaining cycles.

One important observation gathered from tunnel blank measurements was that background levels of PM in the CVS tunnel were found, in some cases, to be at similar levels to the PM levels observed in the CRT vehicle exhaust. This may suggest that a storage and release or re-entrainment of PM mechanism was operating in the CVS tunnel that may bias the conventional legislative gravimetric determination of PM emissions. Thus, before "clean" vehicle technologies continue to be evaluated quantitatively in conventional CVS tunnels, an investigation of the tunnel background measurement approach for low emission vehicles may be appropriate.

Hydrocarbons - In the case of the average total HC emissions illustrated in Figure 8, the CRT consistently yielded emission levels that were near of below detection limits. Results are also tabulated in Table A.3. For the CNG and CNG re-test, NMHC results are reported since methane accounts for a large fraction of the total HC emissions. Although speciation of the NMHC is not reported in this study, Clark et al., [12] have reported that the NMHC's in CNG emissions are ethane, propane, and ethylene. The highest THC emissions for the CRT were measured over the SS at 0.02 g/mi with a zero standard deviation determined over four test sequences (each test sequence consists of multiple cycles) or four SS tests of approximately 40 min each. Coincidently, the same emissions result was obtained for the Diesel OEM over the same cycle. This was the Diesel OxiCat's lowest THC emissions. Over the UDDS, the CRT emissions were half of those measured over the SS (0.01 g/mi). For the remaining cycles, the CRT THC emissions were reported as zero. The THC emissions trend as a function of duty cycle was consistent with the NO_x and PM results for all vehicle configurations, except for the CRT. The NYBC cycle was the most severe for the baseline vehicle where 0.21 g/mi THC emissions were measured. These results were one order of magnitude larger than the emissions over the remaining cycles. Both CNG and CNG re-test emissions of NMHC's were also highest over the NYB cycle (3.27 and 5.44 g/mi, respectively). In addition, the CBD proved to be the second most challenging cycle for the CNG and CNG re-test configurations where 1.26 and 2.55 g/mi NMHC emissions were measured, respectively. Interestingly, in direct contrast to the CRT results, SS operation yielded the lowest NMHC emission levels from the CNG vehicle.

An advantage is also apparent in the use of ultra-low sulfur ECD-1 diesel fuel (11 ppm S content) in combination with the catalyzed muffler in the diesel baseline configuration. The baseline vehicle tested in this study at 0.08 g/mi represents a significant reduction of THC emissions compared to emission levels at 0.18 g/mi from similar buses over the CBD, but fueled by standard Diesel Fuel #1 (247 ppm S content) as reported by Lanni et al. [6].

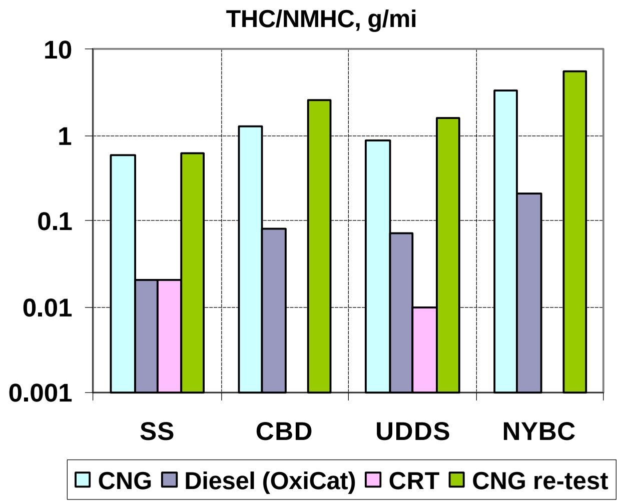

Figure 8. Average Total HC Emissions (NMHC for CNG).

Carbon Monoxide - The emission benefits offered by the catalyst in the CRT were also evident in the CO results shown in Figure 9 and in Table A.3. The catalyst in the CRT was found to yield further reductions in CO emissions relative to the baseline configuration across all cycles. This was especially evident over the NYB cycle where the diesel baseline emissions at 7.16 g/mi were reduced by 94% by the CRT to 0.43 g/mi. The least dramatic reductions of CO emissions by the CRT catalyst occurred over the SS where the baseline emissions of 0.14 g/mi were reduced by 54% to 0.065 g/mi. The CO emissions data over the CBD for the diesel OEM and CRT were in excellent agreement with the results reported by Lanni et al., [6] for similar transit buses equipped with DDC engines. They reported CO emissions of 1.2 and 0.16 g/mi for the OEM and CRT configurations, respectively. These results are nearly identical to the emissions at 1.35 and 0.17 g/mi measured for the OEM and CRT configurations, respectively, in the present study. In general, the baseline and CRT configurations resulted in CO emission levels that were several times lower than those measured in the CNG exhaust. For perspective, over the NYBC cycle, the CNG and CNG re-test generated CO emissions of 24.46 and 36.97 g/mi, respectively. The high CO emissions measured from the CNG vehicle are attributed to the lack of oxidation catalyst control. For all vehicle configurations, the NYBC resulted in the highest CO emissions followed by the emission levels over the CBD cycle.

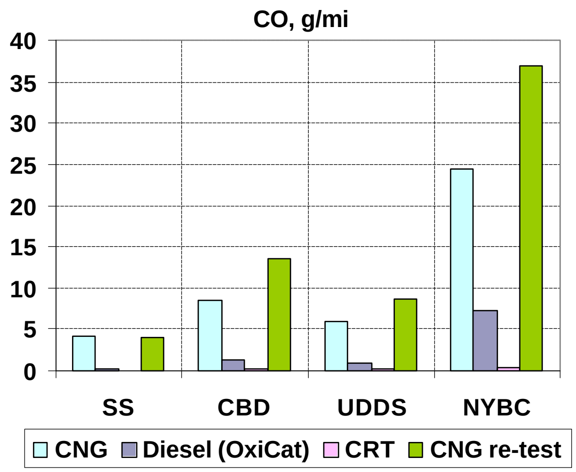

Figure 9. Average CO Emissions

Non-regulated Emission Results

Carbon Dioxide – In general, the CO_2 emissions were consistently slightly higher for the diesel vehicle (in both configurations) compared to the CNG results (both CNG and CNG re-test) as indicated in Table 8 and Figure 10. The highest CO_2 emissions from both diesel and CNG configurations were generated over the NYB cycle. Over the NYBC, the diesel baseline and CRT generated CO_2 emissions at approximately 5400 g/mi while the CNG and CNG re-test results were slightly lower at approximately 5200 g/mi. SS operation resulted in the lowest CO emissions. For this cycle, the diesel and CNG results were approximately 1500 and 1200 g/mi, respectively.

Table 8. Average CO_2 Emissions.

CO_2 Emissions, g/mi	SS	CBD	UDDS	NYBC
CNG	1221.75	2149.82	1519.68	5228.55
Diesel (OEM)	1502.12	2336.11	1714.62	5337.71
CRT	1546.61	2512.99	1750.95	5435.50
CNG re-test	1144.23	2169.05	1550.15	5218.83

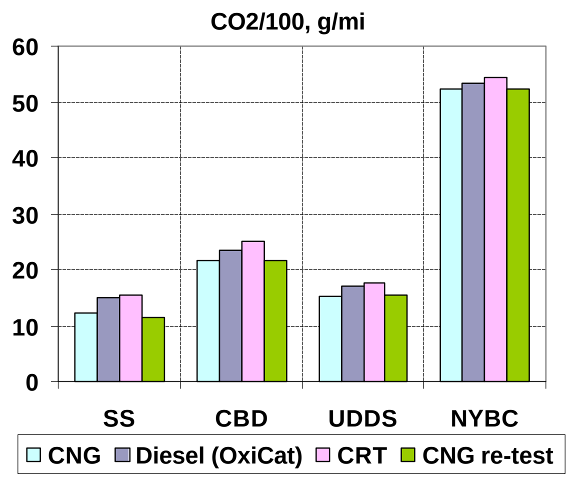

Figure 10. Average CO_2 Emissions.

Nitrogen Dioxide – The CRT system has been described elsewhere and good detailed discussions of the technology have been offered by others [6]. In general, the platinum catalyst that precedes the soot filter in the CRT system efficiently oxidizes exhaust NO to NO_2. It has been shown that the presence of NO_2 is the most useful species for the oxidation of carbon [13]. The NO_2 offers an oxidizing environment in which the carbon light-off temperature requirements are lower compared to standard air. This allows a passive trap system to regenerate in the mild temperature environment characteristic of the typical heavy-duty diesel exhaust. For a given catalyst, the amount of NO_2 oxidized from NO is a function of fuel sulfur content and exhaust temperature. Thus, in principle, for low-sulfur diesel fuel (10 to 50 ppm sulfur), the NO to NO_2 conversion in a CRT can vary from approximately 20% to 70% [13]. Fundamentally and from an occupational perspective, the increase in NO_2 emissions from passive soot traps is of interest due to, for instance, the higher toxicity of NO_2 compared to NO [14]. However, it is likely that the reductions in total PM, HC's, and other toxic emissions offered by the CRT as reported in [6] outweigh the impacts associated with increased NO_2 emissions.

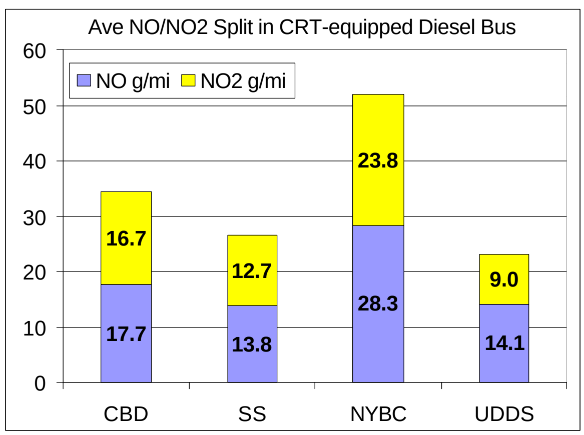

Figure 11. Average NO_2/NO Emissions from CRT-equipped Bus.

The average split of NO_2 and NO emissions for the CRT-equipped configuration as a function of duty cycle is shown in Figure 11. Note that, as reported earlier, the total NO_x emissions were essentially not affected by the CRT. In addition, the CRT used in this study was installed new and "de-greened" prior to testing. A CRT with more mileage accumulation may yield different NO_2 emissions. Furthermore, it may be possible to optimize a DPF and reduce the total NO_2 generated. In terms of percent NO_2 content, as shown in Figure 12, the CBD yielded total NO_x emissions that were composed of nearly 50%

NO_2. In contrast, the NO_2 content in the CRT exhaust over the UDDS cycle was closer to 40%. For comparison, the NO_2 emissions for the baseline configuration (i.e., without the CRT) are illustrated in Figure 13.

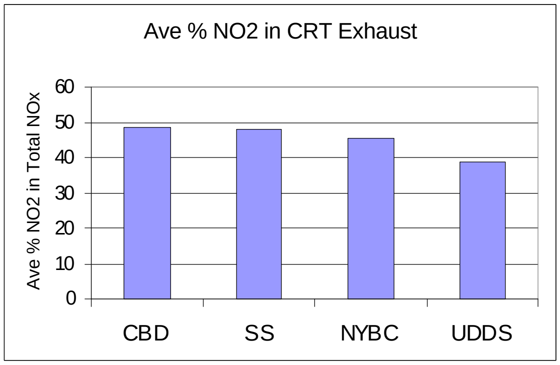

Figure 12. Average Percent NO_2 Content in CRT Exhaust.

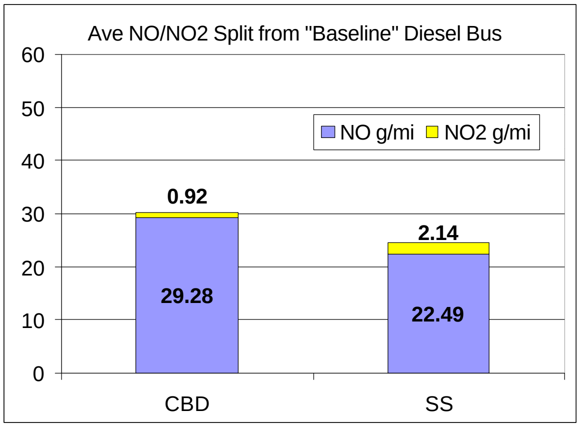

Figure 13. Average NO2/NO Emissions from baseline Diesel OEM Bus.

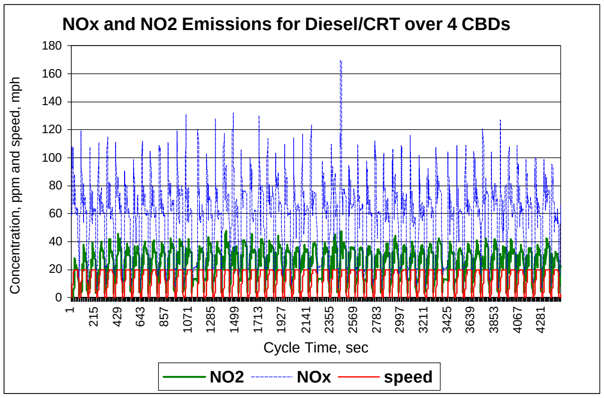

Figure 14. Trace of NO_2 and NO_x CRT Emissions Over CBD Cycle.

A typically modal profile for determining NO_2 and total NO_x emissions over the CBD and generated from the output of two CLM analyzers running in parallel is illustrated in Figure 14. Following the CFR, the modal results were integrated over the duty cycle and reported as average emissions.

CONCLUSIONS

This paper offers a comparison of emissions results over multiple driving cycles. The intend was not to address the adequacy of one cycle versus another, but rather the differences in emissions results due to the inherent differences in the speed-time traces. Findings showed that the NYBC cycle, a short cycle with multiple accelerations, resulted in significantly higher emissions of regulated pollutants, CO_2, and NO_2 (for the CRT only) from all three vehicle configurations investigated in this study. When comparing two variations of the popular heavy duty DDC Series 50 engine in a transit bus application, the CNG version without aftertreatment offers less of an advantage in terms of THC and CO emissions compared to the diesel version fueled by ECD-1 and equipped with a catalyzed muffler. The advantage of CNG over the baseline diesel configuration is clearly lower total PM and NO_x emissions across all cycles. As an emission reduction strategy, the CRT was shown to be efficient for lowering emission levels of total PM, THC, and CO compared to both the Diesel baseline and the CNG configurations. While NO_x emissions were, as expected, higher from the diesel vehicle, the CNG emissions exhibited high variability when comparing the CNG to the CNG re-test results. Thus, the absolute NO_x advantage of the CNG may not be strictly defined for the cycles investigated. Finally, although the CRT did not affect the total NO_x emissions from the baseline configuration, there was a clear shift towards a higher NO_2 fraction across all cycles. The study is on-going and other results will be published as information becomes available.

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DISCLAIMER

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APPENDIX

Table A.1. Test Vehicle Specifications.

	Natural Gas** "CNG"	Baseline Diesel*** "diesel OEM"	Trap Diesel*** "CRT"
Fuel:	Compressed natural gas	Ultra-low sulfur BP/ARCO ECD-1	Ultra-low sulfur BP/ARCO ECD-1
Mileage at start:	19,629	15,169	15,569
MTA Bus#*	5300	3007	3007
Type & Weight	New Flyer Transit 33,150 lbs	New Flyer Transit 30,510 lbs	New Flyer Transit 30,510 lbs
Model Year:	2000	1998	1998
Engine Manufacturer:	Detroit Diesel	Detroit Diesel	Detroit Diesel
Engine Model:	Series 50G	Series 50	Series 50
Displacement/Type:	8.5L/4 cyl/4 stroke	8.5L/4 cyl/4 stroke	8.5L/4 cyl/4 stroke
After-treatment	None	Catalyzed muffler	Johnson-Matthey Continuously Regenerating Trap (CRT™)

* Buses from Los Angeles County Metropolitan Transit Authority fleet
** The CNG bus was re-tested after an additional two months (~1500 miles) of fleet use ("CNG retest").
*** Baseline diesel and trap diesel were the same vehicle.

Table A.2. List of Analytes for Non-regulated EmissionsAnalyses.

PAH's	Carbonyl Compounds	Hydrocarbon Speciation
Particle Associated	Formaldehyde	1,3-Butadiene
Benzo(g,h,i)perylene	Acetaldehyde	Benzene
Dibenz(a,h)anthracene	Acrolein	Toluene
Indeno(1,2,3-cd)pyrene	Acetone	Ethylbenzene
Perylene	Propionaldehyde	m,p-Xylene
Benzo(a,e)pyrene	Butyraldehyde	Styrene
Benzo(b,k)flouranthene	Methyl Ethyl Ketone	o-Xylene
Chrysene	Methacrolein	
Benz(a)anthracene	Benzaldehyde	
Semi-volatile	Crotonaldehyde	
Pyrene	Valeraldehyde	
Flouranthene	m-Tolualdehyde	
1-methyl phenanthrene	Hexanal	
Anthracene		
Penanthrene		
Flourene		
Volatile		
2,6-dimethyl naphthalene		
Acenaphthene		
Acenaphthylene		
Biphenyl		
1-methyl naphthalene		
2-methyl naphthalene		
Naphthalene		

Table A.3. Average test sequence results based on multiple cycle runs. At a minimum, averages were for two test sequences, each test sequence was composed of at least two individual cycles.

AVERAGE TEST SEQUENCE VALUES											
Test	**Bus**	**PM**		**THC**		**CO**		**NOx**		**NMHC**	
Cycle	**Configuration**	**mg/mi**	**STDEV**	**g/mi**	**STDEV**	**g/mile**	**STDEV**	**g/mile**	**STDEV**	**g/mile**	**STDEV**
CBD	CNG	39.88	12.52	10.09	0.79	8.50	0.46	15.42	1.21	1.26	0.09
	Diesel (OEM)	119.03	6.97	0.08	0.01	1.35	0.04	30.21	1.13	N/A	N/A
	CRT	14.15	0.35	0.00	0.00	0.17	0.00	31.14	0.57	N/A	N/A
	CNG-retest	33.45	1.2	13.82	0.09	13.63	0.23	22.66	0.69	2.55	0.19
SS	CNG	22.90	1.98	4.62	0.09	4.23	0.00	6.76	0.43	0.58	0.02
	Diesel (OEM)	23.3	6.22	0.02	0.00	0.14	0.04	24.90	0.88	N/A	N/A
	CRT	3.43	0.59	0.02	0.00	0.065	0.01	26.49	0.65	N/A	N/A
	CNG-retest	N/A	N/A	2.74	0.22	4.02	0.35	16.20	7.30	0.60	0.09
NYBC	CNG	92.05	19.73	27.39	0.24	24.46	0.28	19.45	0.21	3.27	0.21
	Diesel (OEM)	631.00	N/A	0.21	N/A	7.16	N/A	51.02	N/A	N/A	N/A
	CRT	95.90	21.57	0.00	0.00	0.43	0.03	52.06	1.28	N/A	N/A
	CNG-retest	102.15	21.14	26.88	2.32	36.97	0.26	39.42	0.66	5.44	0.44
UDDS	CNG	23.07	2.81	7.78	0.23	5.99	0.31	11.70	0.66	0.86	0.05
	Diesel (OEM)	90.63	5.43	0.07	0.02	0.99	0.06	24.20	0.80	N/A	N/A
	CRT	16.63	1.96	0.01	0.00	0.15	0.02	23.14	0.78	N/A	N/A
	CNG-retest	23.67	2.85	7.77	0.30	8.70	0.08	16.96	0.52	1.59	0.06